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FERRORESONANCE TESTS ON T14 TERTIARY AT CLAIREVILLE TS

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A series of full-scale switching operations was performed on the T14 autotransformer at Claireville TS. These operations were intended to duplicate a reported ferroresonance condition on T14 28-kV tertiary; however, results show that ferroresonance was not established. Analysis of test results shows that PT remanence after switching T14 off-potential was not sufficient to initiate a ferroresonance condition on the subsequent closing operation. Such a condition which requires a high PT remanence and a particular pole-closing sequence on subsequent energization is not a very likely occurrence. However, in view of the fact that ferroresonance has been encountered before and its possibility cannot be ruled out, a solution of a resistor connected across the PT secondary is proposed.

1. INTRODUCTION

A ferroresonance condition was experienced at Claireville TS in June 1985. The circumstances under which the problem occurred were reported as follows /1/. The station service transformer was out of service (Figure 1), leaving the T14 tertiary winding (28 kV) supplying a short length of bus. Three magnetic potential transformers (PT) rated 34.5 kV are connected wye-grounded on the 28-kV bus. The secondaries of the PTs are connected to auxiliary PTs which are connected in open delta for sensing voltage unbalance on the ungrounded 28-kV system. With this electrical arrangement, when the autotransformer was energized from the 230-kV side, a ground alarm was annunciated. We were subsequently asked by Transmission Operations Division to study the problem and to propose solutions to prevent future occurrences.

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In response to this request, methods for suppressing ferroresonance were investigated and validated by computer simulations /2/. A method involving connection of a damping resistor across the spare-secondary windings of existing PTs connected in open-corner delta was recommended. In addition, low-voltage excitation tests were performed on T15 PTs at Claireville TS to obtain data for estimating the damping resistor value. Full-scale switching operations were conducted on T14 autotransformer to duplicate the reported condition /1/ and to demonstrate effectiveness of the damping-resistor solution.

This report presents results of full-scale switching operations and low-voltage excitation tests. It also gives an assessment of the test results and estimates the damping resistor value.

2. FULL-SCALE SWITCHING OPERATIONS

2.1 Description

A series of switching operations was performed on T14 to establish a sustained ferroresonance condition on the tertiary 28-kV system. The test circuit shown in Figure 2 was arranged to be identical to that reported for ferroresonance (Section 1). Since ferroresonance necessarily involves repetitive saturation of PT core /2-7/, the strategy for these switching operations was to cause a PT to saturate when T14 was energized. This was attempted by controlling the point-on-wave breaker tripping to leave as high a remanence as possible on a PT, and then adjusting the point-on-wave closing to accumulate the maximum possible flux on that PT.

Three phase-to-ground PT voltages were measured from one set of T14VT3 PT secondaries and integrated to obtain flux linkages. The spare-secondary windings of PTs were connected in open delta and connected to the damping-resistor switching system which monitored the open-delta voltage and current. Three-phase PT currents were measured by CTs mounted on the PTs. T14 autotransformer inrush and magnetization currents were recorded from T14CT10 CTs. Also, Rϕ terminal voltage was monitored from T14CVT1. The recording instruments used were 36-channel electromagnetic oscillographic, 14-channel tape recorder and 12-channel data acquisition system. An automatic sequence controller was used to control the switching sequence and the point-on-wave closing and opening.

2.2 Results

A total of 17 close-open switching operations were performed on T14 autotransformer. These operations covered one full cycle of points-on-wave opening and closing. Ferroresonance, however, was not established by these controlled switchings. Table I lists the highest remanence encountered after switching the transformer off-potential, and shows the peak flux value attained on the subsequent closing operation.

The test results show that the highest PT remanence encountered was 0.34 pu in Test 15 (Figure 3). This corresponds to about 72% of the peak steady-state PT flux (0.47 pu of PT rating). With this remanence on Rϕ PT, the point-on-wave closing was adjusted to maximize flux on this PT. Table I shows that the peak flux of this PT reached 1.20 pu. The increase in flux is therefore

about 0.86 pu which is about 91% of the increase possible theoretically (0.94 pu of PT rating assuming 28-kV bus voltage). The point-on-wave closing was therefore controlled as desired, but ferroresonance was not established.

TABLE I

Measurements of T14 PT Flux

Test No.	Phase of Max. Flux	Remanence (pu of PT rating)	Peak Flux after Energizing (pu of PT rating)
1	Wϕ	+ 0.05	- 0.75
2	Rϕ	- 0.06	- 0.94
3	Wϕ	– 0.20	– 0.90
4	Rϕ	– 0.06	– 0.56
5	Bϕ	+ 0.12	+ 0.96
6	Bϕ	+ 0.04	+ 0.94
7	Wϕ	- 0.05	- 0.90
8	Rϕ	- 0.19	- 1.07
9	Bϕ	+ 0.15	+ 0.93
10	Rϕ	- 0.19	- 1.07
11	Rϕ	- 0.08	- 0.85
12	Rϕ	+ 0.01	+ 0.94
13	Wϕ	- 0.08	- 1.03
14	Bϕ	+ 0.15	+ 0.93
15	Bϕ	- 0.34	- 1.20
16	Bϕ	+ 0.19	+ 0.97
17	Rϕ	+ 0.27	+ 1.09

2.2 Analysis

Results of Test 15 can be analyzed using the dc-excitation measurements given in Appendix I. These measurements show that the knee point of the PTs is about 1.18 pu, while the peak flux encountered in Test 15 was about 1.2 pu. However, this was not sufficient to initiate ferroresonance on the T14 tertiary. Since the PT flux reached its peak when voltage was small (being about 90° out-of-phase), 3ϕ PT voltages remained balanced as shown in Figure 4.

Computer simulations showed that a sustained ferroresonance condition could be established by the switching condition of Test 15 /2/ if PT knee point was 1.03 pu (or lower). Otherwise, the estimated remanence on one of 3 PTs needs to be higher than 91% of the theoretical-maximum steady-state PT flux (0.47 pu). Previous computer studies assumed a fairly low knee point (1.0 pu) and small saturated inductance (6 H) due to the lack of field measurements /2/. These assumptions enhanced the occurrences of ferroresonance conditions in the previous computer simulations.

3. ASSESSMENT

The test analysis in Section 2 shows that the PT remanence after switching T14 off-potential was not sufficient to initiate a sustained ferroresonance condition on the subsequent closing operation, because T14 PT has a high knee point. For such a condition to occur, it requires a very high PT remanence as well as a particular pole-closing sequence on subsequent energization. Therefore, a sustained ferroresonance on the T14 tertiary is not a very likely occurrence.

However, there could be system conditions for PTs to accumulate a high remanence after switching T14 off-potential, such as a fault encountered on T14 tertiary. Also, the actual point-on-wave of opening of T14 230-kV breaker may vary even with an identical tripping signal. This statistical opening phenomenon imposed a difficulty for controlling PT remanence on the limited switching operations. It is possible a particular breaker opening leaves a PT with high remanence which would lead the system into a sustained ferroresonance.

In view of the fact that ferroresonance has been encountered before, and its possibility cannot be ruled out, a solution consisting of a resistor connected across the open-delta connection on PT secondary windings is proposed. An 80-Ω, 500-W resistor can be used. This resistor value is estimated from an empirical formula and results of low-voltage excitation tests shown in Appendix II.

4. SUMMARY & CONCLUSIONS

(a) A series of full-scale switching operations was performed on the T14 autotransformer at Claireville TS. The switching operations covered a wide range of points-on-wave tripping and closing T14 230-kV breaker, intended to establish a sustained ferroresonance on T14 28-kV system.

(b) The maximum flux which can be accumulated on one PT by controlled switching operations was only slightly higher than the estimated PT knee point. It was not sufficient to initiate a sustained ferroresonance.

(c) The test analysis shows that a sustained ferroresonance condition on T14 28 kV system is not a very likely occurrence.

(d) Dc excitation tests were performed on T15 PTs at Claireville TS. 3ϕ PT magnetization characteristics were measured. These test results are post-processed to obtain values of knee point, magnetization inductance, leakage inductance, and air-core inductance. These values have been used for ferroresonance studies using EMTP.

(e) The value of damping resistor is estimated based on an empirical formula and the excitation-test results. An 80-Ω, 500-W resistor is needed for the control of ferroresonance at Claireville TS. This resistor can be connected across the open-delta connection of the spare-secondary windings of existing T14 PTs. Its effectiveness for controlling ferroresonance has been checked by computer simulations.

5. RECOMMENDATIONS

On the basis of full-scale switching tests, a sustained ferroresonance condition on the T14 tertiary, even without the station-service transformer, is not a very likely occurrence. Therefore, the 28-kV system may not need a damping resistor. However, in view of the fact that ferroresonance has been encountered, and its possibility cannot be ruled out, a solution of connecting an 80-Ω, 500-W resistor across the PT secondary windings is proposed.

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(6) A. Narang, Memo to R.E. Westwood, "Ferroresonance on Milton X Trafalgar 500-kV Circuit," June 8, 1982.

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APPENDIX I

LOW-VOLTAGE EXCITATION TESTS

1. Instrumentation

Low-voltage excitation tests were performed on T15VT3 PTs at Claireville TS. Key components in the test instrumentation are shown in Figure 5. A 12-bit, 16-K digital oscilloscope was used to obtain digital records of measurements. A 350-V, 1.5-A power supply was used to provide the variable dc excitation. PT flux linkage was derived using an analog integrator with a low-drift operational amplifier (0.3 μV/month). PT current was measured using a differential amplifier. Surge diverter, spark gaps and fuses were used to provide the necessary surge protection.

Prior to starting measurements, the offset error of the integrating operational amplifier was adjusted (for mutual- and self-inductance measurements) to minimize integrator drift. For self-inductance measurements, the compensation resistor was set to cancel winding resistive voltage drop. For measurements of the magnetization characteristics, the PT HV winding was excited by slowly varying the power supply output (< 0.01 Hz). PT flux linkage versus current was measured using Nicolet scope.

2. Measurements

Figure 6 shows hysteresis measurements of 3ϕ T15VT3 PTs. These were mutual-inductance measurements with excitations on PT HV windings and flux-linkage measurements on LV terminals. The per-unit system used to displayed these measurements are based on PT ratings (34.5 kV, 5 kVA). From these measurements, the PT saturated inductance is found to be 0.05 pu, PT magnetization inductance is 2900 pu, and the hysteresis loss is 0.01 pu. Rϕ PT has a knee point of 1.03 pu which is lower than that of 1.18 pu for Wϕ and Bϕ PTs. The winding resistance for each PT is 0.008 pu.

Figure 7(a) shows the self-inductance measurement on Bϕ PT with both excitation and flux-linkage measurement on HV winding. A comparison of PT magnetization characteristics from the self- and mutual-inductance measurements is given in Figure 7(b). The air-core inductance obtained from the saturated slope of the self-excitation measurement is 0.076 pu. The leakage inductance is 0.026 pu which is the difference of the saturated slopes between the self and mutual measurements. These test results have been used for computer studies using ElectroMagnetic Transients Program /3/.

APPENDIX II

DAMPING RESISTOR ESTIMATION

The value of damping resistor required for controlling ferroresonance can be estimated using an empirical formula /2,4/:

$$R_{damping} = 10^5 L_s / N^2$$

Here L_s is PT saturated inductance (H), and N is the turns ratio. The nominal turns ratio for T15VT3 is 240:1. Based on the excitation measurements of T15 PT saturated inductance (45 H given in Figure 6), the damping resistor value could be as high as 80 Ω. The effectiveness of this damping resistor for controlling ferroresonance at Claireville TS has been checked by EMTP simulations /3/. The thermal duty on this resistor connected across the PT open-corner delta would be minimal due to ferroresonance, as compared to that associated with a ground fault on the 28-kV bus which could last indefinitely. This resistor would dissipate about 500 W when a single line-to-ground fault occurs on the bus. This load will be shared by two PTs and, therefore, one PT would only carry 5% of its rated 5-kVA thermal capacity.

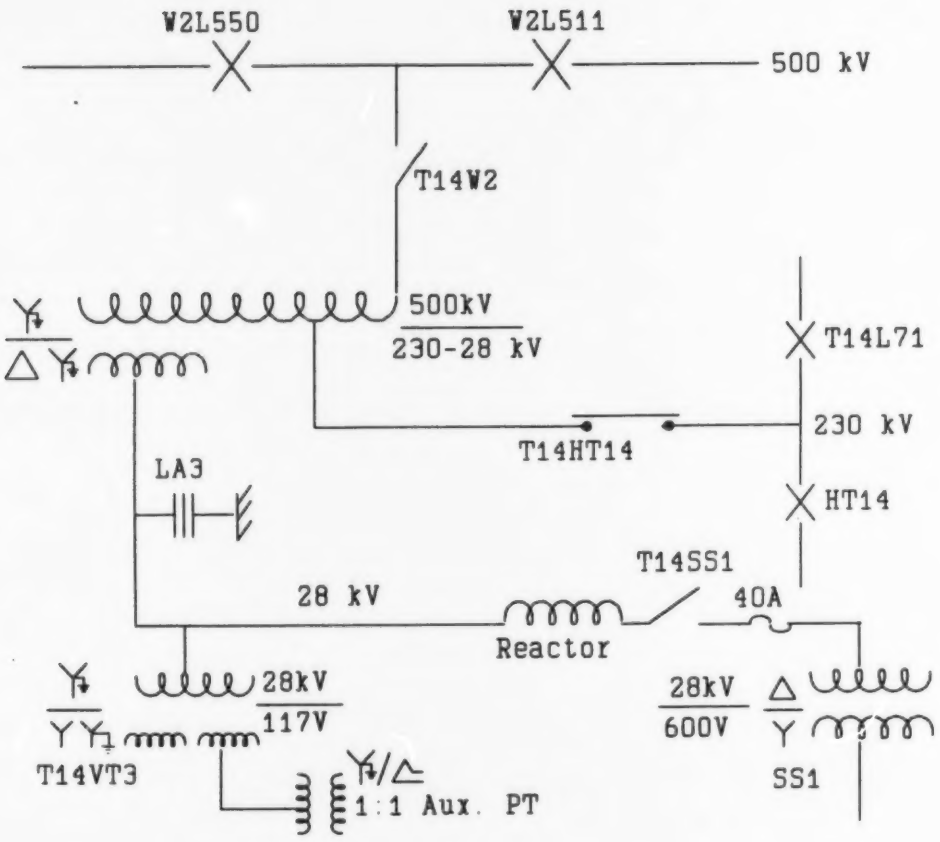


Figure 1 Relevant section of Claireville T15

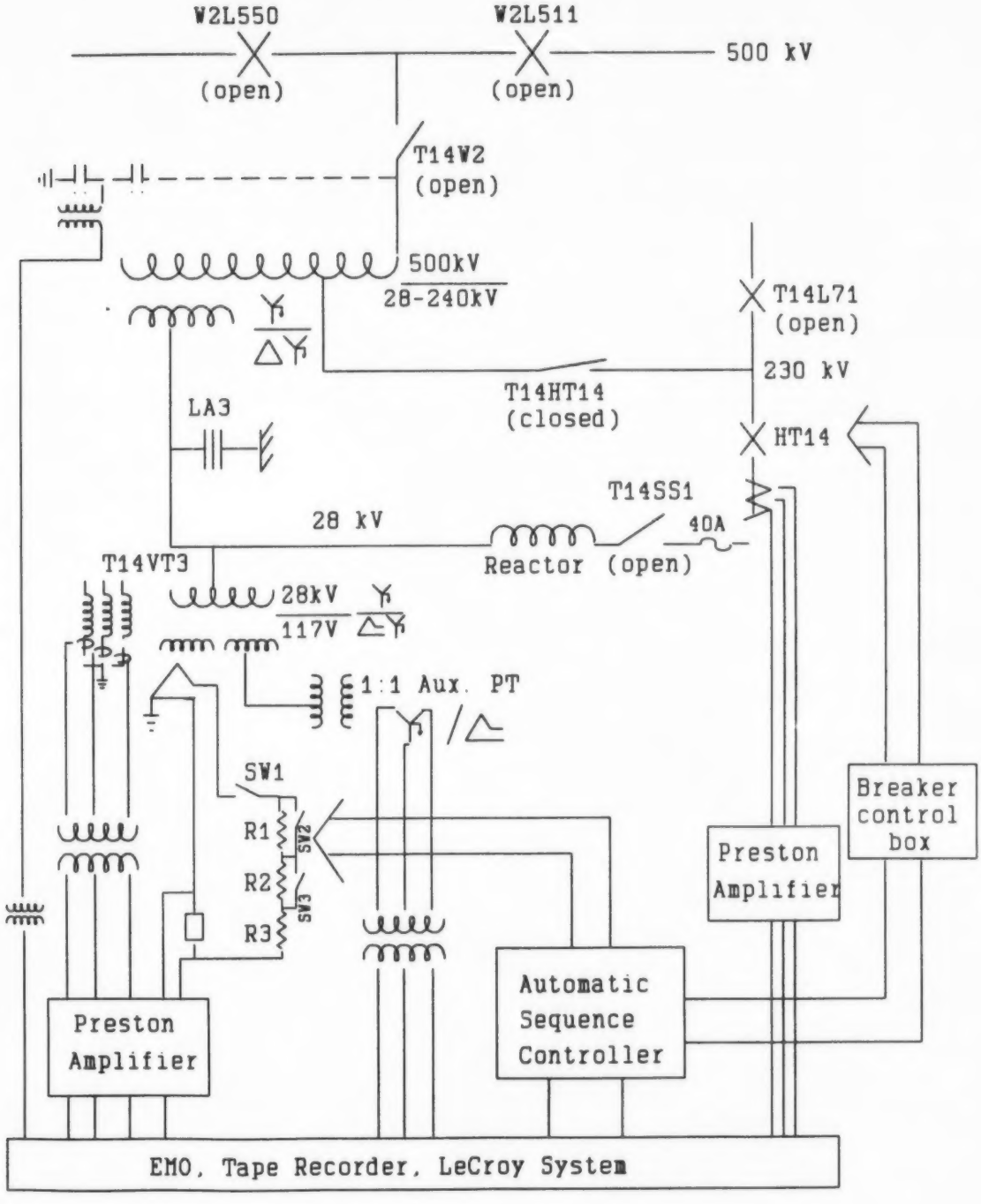
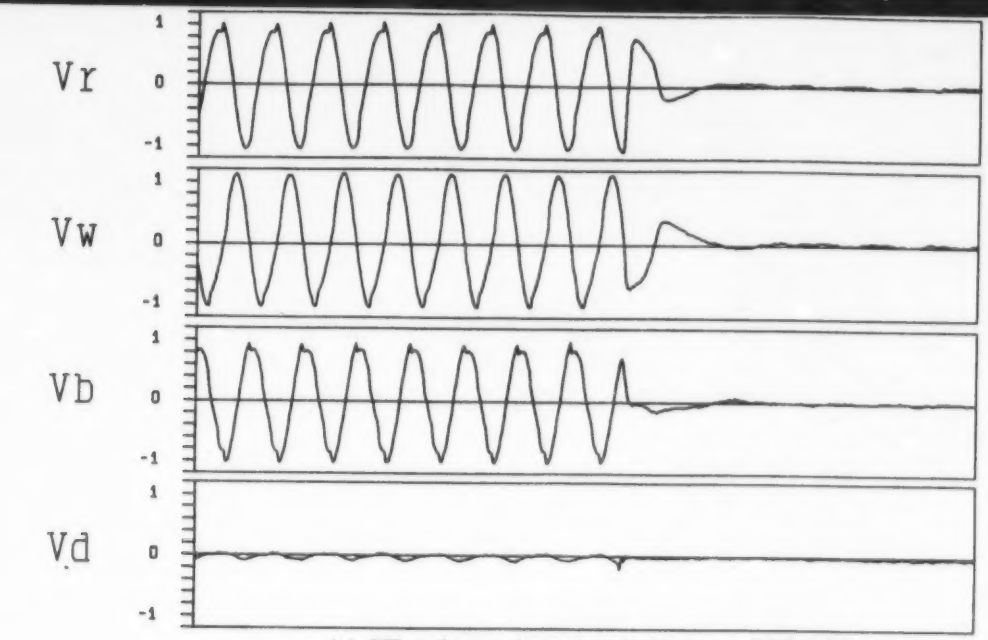
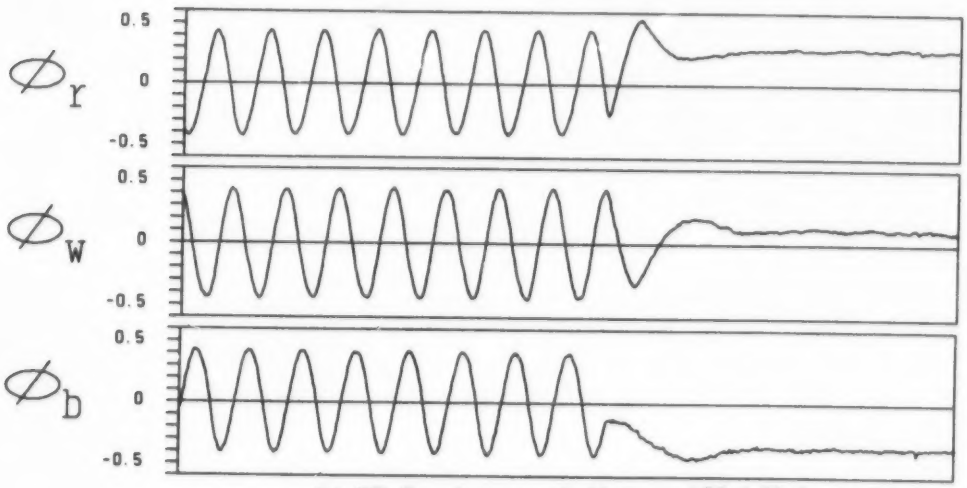


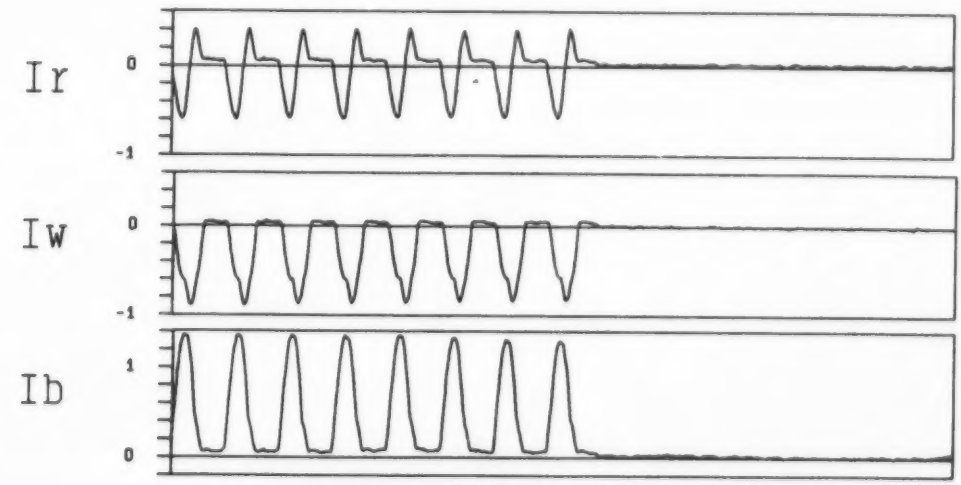
Figure 2 Schematic switching test circuit



(a) PT voltages in per unit (1 pu = 22.9 kV)

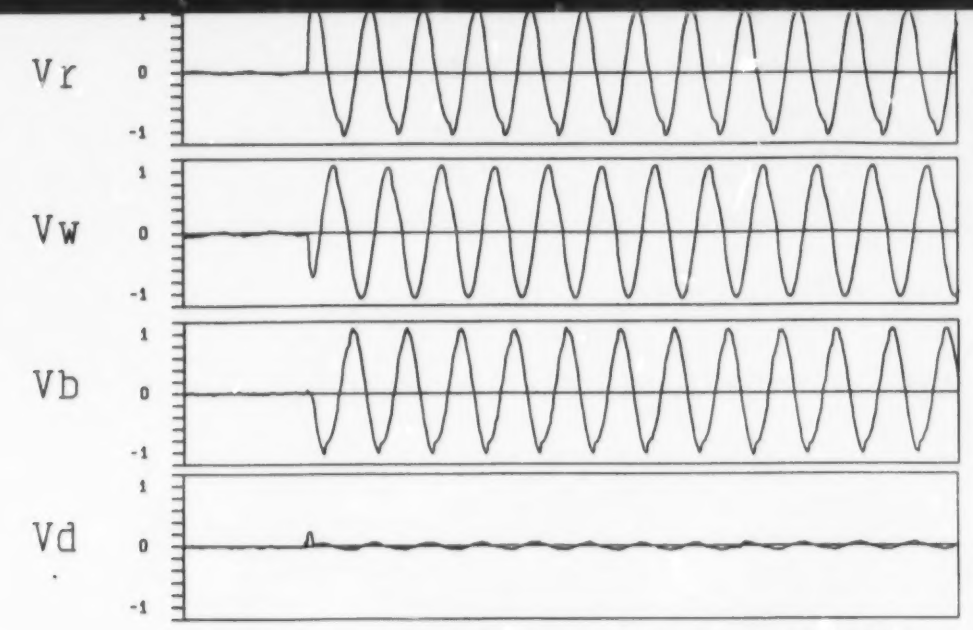


(b) PT flux in per unit (1 pu = 129.4 V.s)

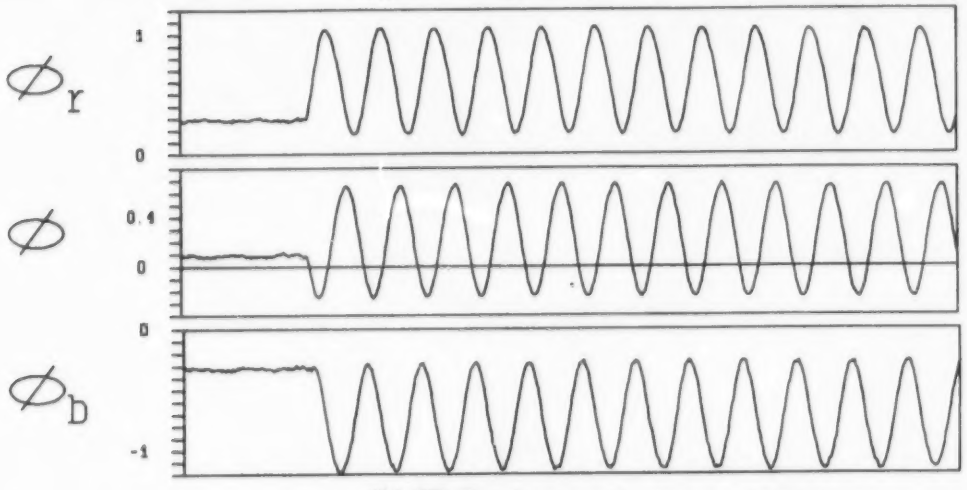


(c) T14 currents in per unit (1 pu = 1.8 kA)

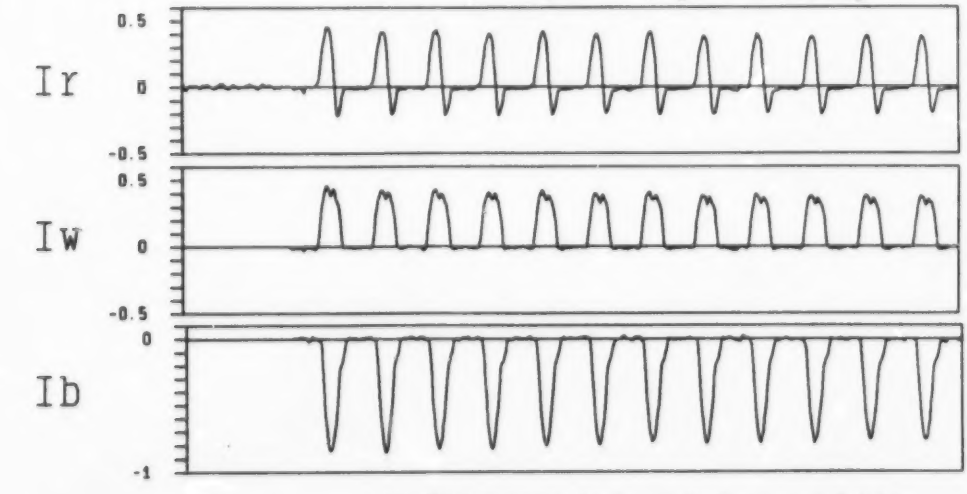
Figure 3 Test-15 results for T14 tripping



(a) PT voltages in per unit (1 pu = 22.9 kV)



(b) PT flux in per unit (1 pu = 129.4 V.s)



(c) T14 currents in per unit (1 pu = 1.8 kA)

Figure 4 Test-15 results for T14 closing

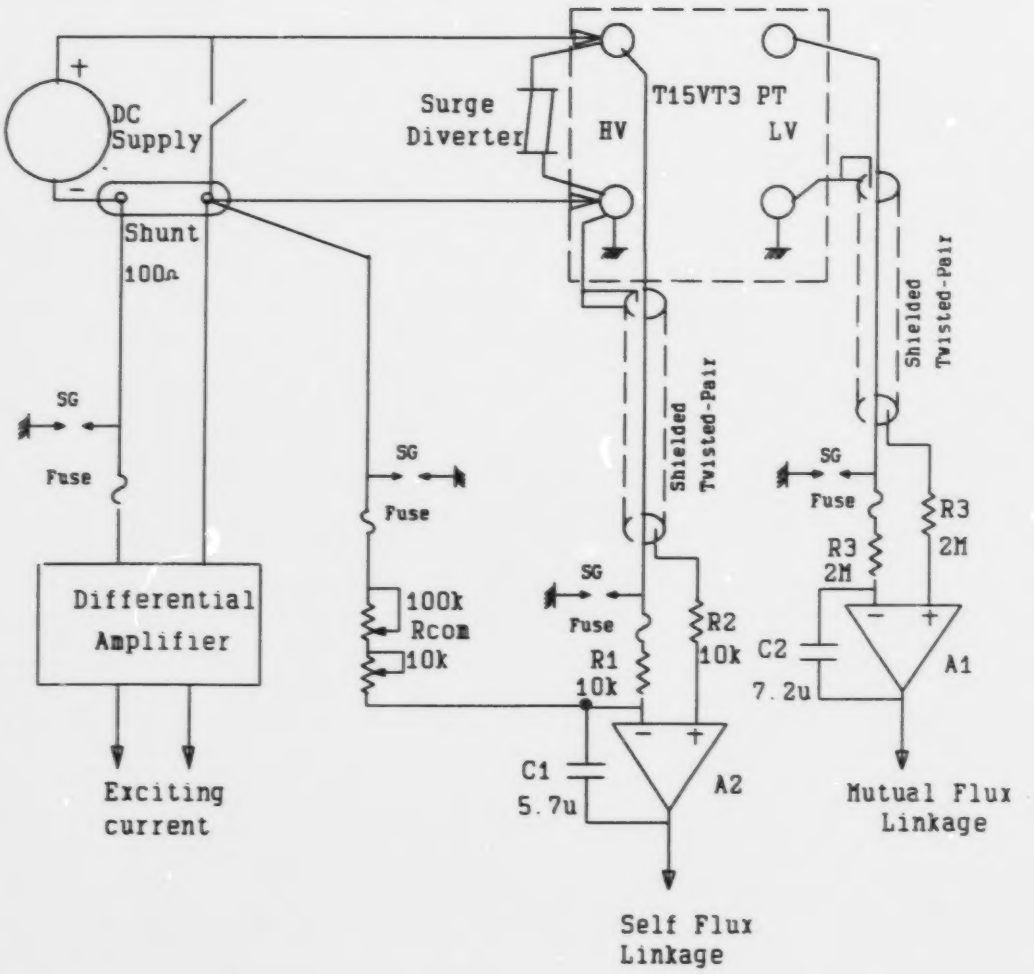


Figure 5 Schematic dc-excitation test circuit

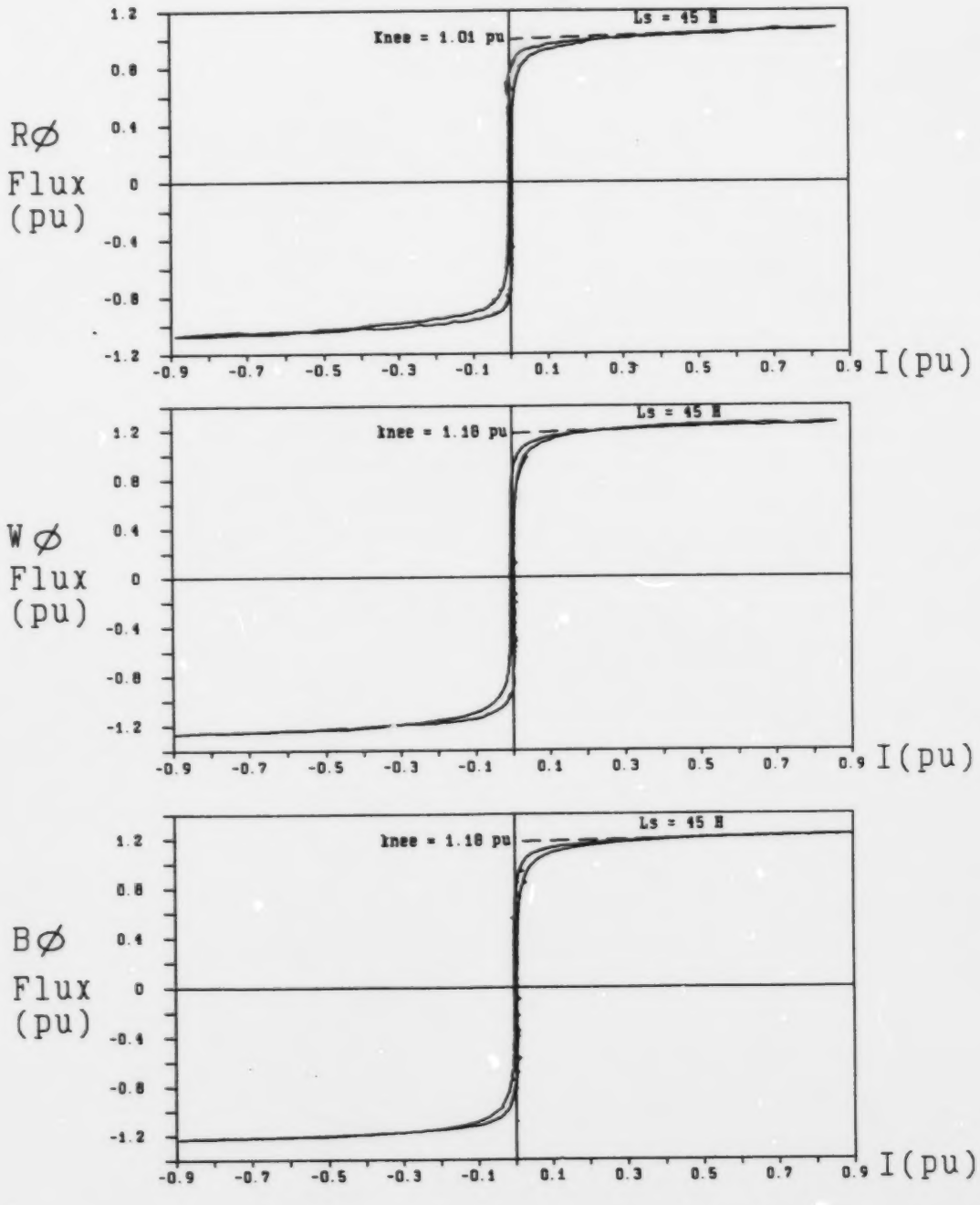
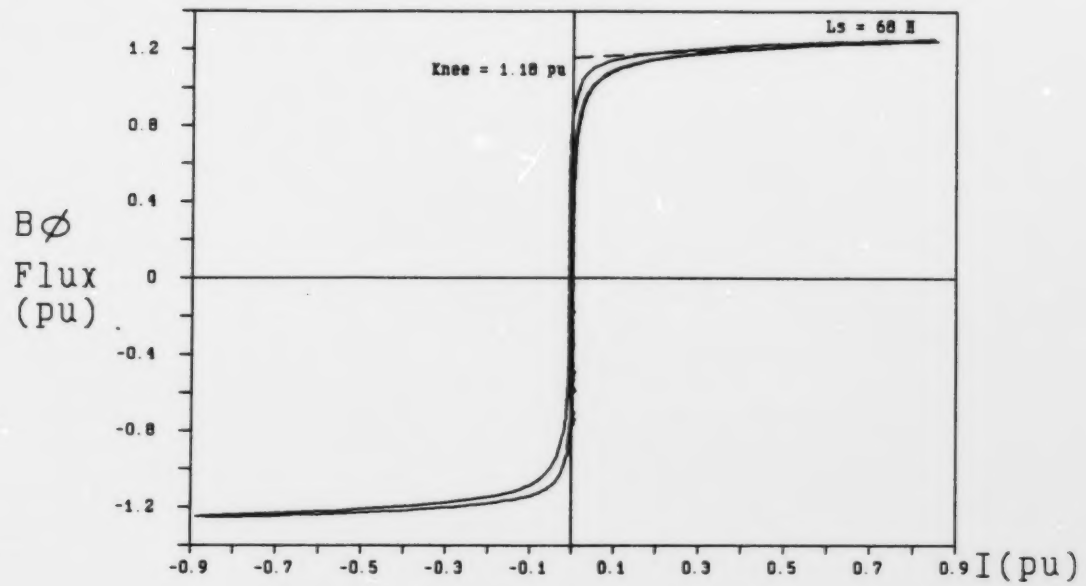
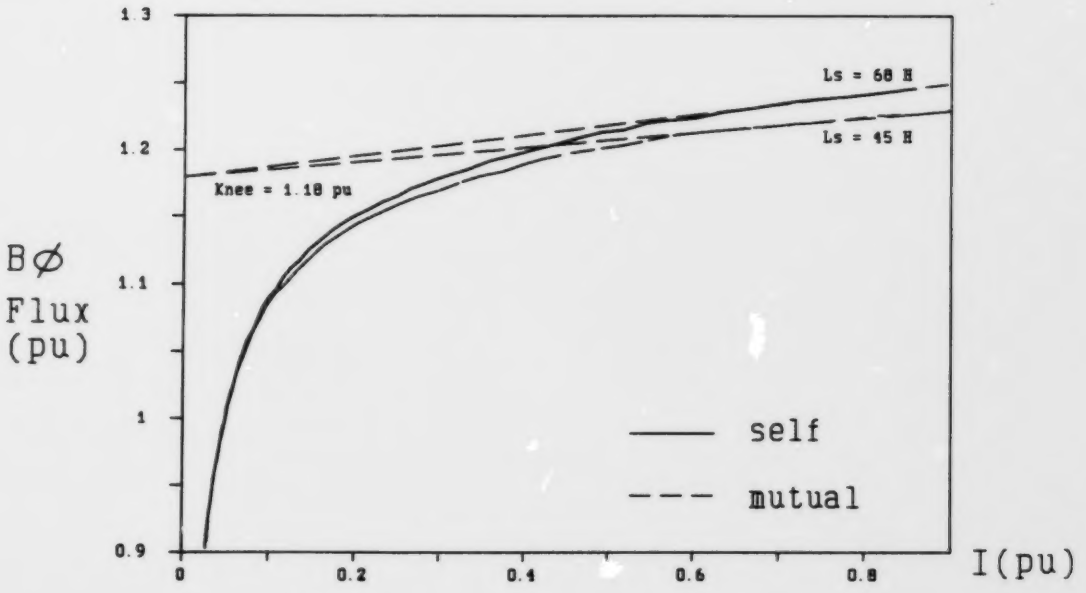


Figure 6 Hysteresis measurements of T15 PTs with excitation on HV windings and flux measurement on LV terminals.

(Flux linkage on LV winding, 1 pu = 0.54 V.s
Excitation current on HV winding, 1 pu = 145 mA)



(a) Excitation and flux measurement on HV winding



(b) Comparison of self and mutual inductance measurements

Figure 7 Hysteresis measurements of B-phase PT

(Flux linkage on HV winding, 1 pu = 129.4 V.s
Excitation current on HV winding, 1 pu = 145 mA)